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Comparison of methodologies for cloud cover estimation in Brazil - A case study

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ABSTRACT

Clouds are the major modulator of the shortwave and longwave radiation components of the Earth's energy balance and, as such, help to regulate the planet's temperature. In the energy sector, clouds are a source of instability in the generation of energy using solar technologies. This study aims at comparing three approaches to get cloud cover information in the Southeastern region of Brazil during the period of approximately three months. The first method, assumed as reference, uses all-sky camera pictures for the cloud cover estimation. The other two methodologies use downward longwave radiation with surface meteorological data and geostationary satellite data. Both methods presented good agreement with the camera for clear sky and overcast conditions, with probabilities of detection of 92.8% and 80.7% for the longwave method and 93.3% and 87.6% for the satellite method, respectively. The major problem occurs with the broken-clouds sky scenario, with probabilities of detection above 38%, where each method has its own specificity, such as, longwave emissivity of the atmosphere, spatial resolution and view geometry. The long-wave method has the minor R correlation with the camera (87%) when compared with the satellite method (93%) and requires a daily normalization, which make it not usable for instantaneous measurements. Regarding the satellite method, the most important issue is the spatial resolution, which has the major impact on the broken-clouds sky scenarios. The cloud masking works properly for large clouds with, at least, the size comparable to the satellite image pixel. Furthermore, the method using the all-sky camera also needs to be improved, because it presented some deficiencies, like very bright areas around the sun, sometimes identified as clouds, leading to cloud cover overestimation.

Introduction

The understanding of the several factors influencing the Earth's energy balance is fundamental for assessment of the Earth's climate and its variability. Clouds are the major modulator of the shortwave and longwave radiation components of the Earth's energy balance and, as such, help regulate the planet's temperature. In general, high clouds act as greenhouse gases, increasing the longwave radiation (LW) at the surface and warm up the atmosphere, while low clouds have a cooling effect by reflecting the solar radiation back to space (Liou, 2002; Malek, 1997). Clouds can even enhance the solar radiation at surface, sometimes to values higher than the ones observed at the top of the atmosphere. This effect happens due the reflection by the cloud edges and/or forward scattering of the radiation by the clouds nearby when the Sun is not obstructed by them (Antón et al., 2011; Calbó, 2005; Tzoumanikas et al., 2016).

In the energy sector, clouds are a source of instability in the generation of energy using solar technologies. Clouds shade the flow of solar energy by their scattering and absorbing effects, causing severe fluctuations in the energy output of photovoltaic plants (Ari & Baghzouz, 2011; Lave, Reno, & Broderick, 2015; Perez et al., 2016). Also, the solar radiation fluctuation ends up producing transients that are incompatible with the established safety standards for the electricity distribution system, including network voltage variability, and insufficient generation to meet the momentary demand of the electrical system (Kleissl, 2013). In addition, they can produce rapid variations in the receiver temperature that may lead to thermal stress of the devices (Kazantzidis et al., 2012).

Because of this, the clouds have attracted increasing interest in the solar energy sector. The first method for assessment of cloud coverage was the visual observations made by operators of meteorological stations, and it is still used today. The method classifies clouds according to visual analysis of shape and appearance, dividing the sky into eight parts (octas) estimating the cloud coverage (ROBAA, 2008; Werkmeister et al., 2015). Because of the high subjectivity of the method, nowadays, several authors reported different ways for estimating the amount of clouds in the sky in a more objective way. Some authors report methods using downward longwave radiation, along with other meteorological parameters acquired at the surface (Dürr & Philipona, 2004; Malek, 1997; Marty & Philipona, 2000). Others investigate the

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cloud cover conditions based on all-sky camera images (Kazantzidis et al., 2012; Long et al., 2006; Neto et al., 2010) and/or on satellite data (Escrig et al., 2013; Liang & Yuan, 2016).

There are several difficulties in combining satellite with ground-based data when related to measures of cloudiness. Differences in both spatial and temporal resolutions can be cited. In addition, satellites feature instantaneous measurements at small solid angles, while ground measurements are made at large solid angles from the sky dome (Espinar et al., 2009). Also, multiple cloud layers, may lead to misclassifications; e.g. high clouds appear sooner at the all-sky camera images than low clouds at the same distance, while height has no effect for the satellite analysis (Escrig et al., 2013).

Many authors have worked comparing different methods for cloud analysis. Wacker et al. (2015) compared different methods for the estimation of the total cloud cover over Switzerland. The methods used all-sky cameras, downward longwave radiation, visual observations, the MSG satellite and ceilometers. With direct comparisons of the results in octas, the results indicated that the automatic methods underestimated the nebulosity estimated by the observer; however, the method using the all-sky camera obtained the closest results. In the comparison between the automatic methods, the data with the better agreement were those obtained with the camera and the MSG satellite. In 52% of cases, the two methods obtained the same result, while errors within ±1 or ±2 octas were 72% and 84%, respectively.

Escrig et al. (2013) compared different cloud situations over Almería, Spain, using the MSG satellite and an all-sky camera. Their satellite algorithm always detected clouds when the camera classified a condition as overcast (over 7 octas) and never classified as overcast when the camera classified as cloudless (below 1 octa), both with >90% of agreement. For partially cloudy situations the method had approximately 75% of agreement. Werkmeister et al. (2015) made the same comparison for Hannover (Germany), but they classified the situations differently: the overcast condition was stipulated for cloud fractions over 5 octas, the cloudless condition for fractions below 3 octas and broken sky from 3 until 5 octas. For overcast situations, the satellite probability of detection presented very good skill (94%), for cloudless the skill was good (72%), but for intermediate fractions the skill was unsatisfactory (12%).

This study aims at comparing three approaches to get cloud cover information in the Southeastern region of Brazil. The methodologies use downward longwave radiation with surface meteorological data, geostationary satellite data and all-sky camera images. The comparative evaluation assumed the all-sky camera method as the reference methodology, because of the better data resolution.

Data and methods

Study area – Cachoeira Paulista

The surface measurement site is located in one of the campuses of the National Institute for Space Research (INPE), in the city of Cachoeira Paulista (22° 41′ 22.65″S; 45° 00′ 22.8″W). The annual rainfall average ranges from 1500 mm to 1700 mm and presents an annual cycle with a wet season (from October until March) that concentrates most of the precipitation (~190 mm/month) and a dry season (from April until September) with very low rainfall (~55 mm/month) (Climatempo, 2017). This also influences the mean cloud cover fraction in the region, which has a mensal mean around 70% in the wet season and 50% in the dry season, according to visual observations (INMET, 2009). The occurrence of cold fronts is very common during the dry season (wintertime), which brings most of the nebulosity for this season. The region is also affected by the Intertropical Convergence Zone and the natural convection is very typical during the summer season (wet season) (Nunes, Vicente, & Candido, 2009).

Determination of cloud cover fraction using the all-sky camera

The all-sky camera SRF-02 (EKO Instruments) is a digital camera with a fish eye objective and 180° field of view. The camera is encased in a weatherproof housing with a heater system for temperature stability. The user can remotely set up the image acquisition parameters using a desktop computer through TCP/IP connection. The instrument is operating at the roof of the Laboratory of Meteorological Instrumentation (LIM) from INPE. The image acquisition was performed in a 10-min interval during the year of 2016, from July 4th to September 30th. The camera took two sky images with different light exposure: one normal exposed (NE) and one underexposed (UE). The EKO instrument provides the Cloud Cover Fraction, hereafter called CCF_{Cam}, using the company's software package to identify clouds and calculate the cloud cover fraction for each acquired image. In reason of the hazy sky and the presence of some obstacles close to the horizon line, the image pixels with zenith angles larger than 70° were discarded. Then, assuming an average cloud height of 3 km, the acquired image covers about 250 km^2.

The EKO software algorithm calculates the ratio blue/red + blue/green (BRBG) in both NE and UE pictures. The pixels presenting BRBG values smaller than a threshold are classified as cloudy. Fig. 1 shows a typical sky image (on the left,) and the corresponding cloud identification image (on the right).

Determination of cloud cover fraction using Downward Long-Wave Radiation (LW) data

The methodology to estimate the cloud cover fraction using Downward Long-Wave Radiation (LW) is based on studies described by Malek (1997) and Marty and Philipona (2000). Besides LW data, the method requires information about air temperature, relative humidity and atmospheric pressure. For this study, all data were acquired by an automated weather station operating at the same location of the EKO all-sky camera from July 4th to September 14th, 2016.

Monteith and Unsworth (1990) demonstrated that the LW data could be evaluated as a sum of the sky emittance and the cloud emittance. Moreover, the cloud emittance depends on the cloud cover fraction (CCF_{LW}) and the cloud base temperature (T_c) in K, as showed in Eq. (1).

$$LW = \epsilon_c.\sigma.T_a^4 + \text{CCF}_{\text{LW}}.(1{-}\in_c).\sigma.T_c^4 \tag{1}$$

Eq. (2) describes the relationship between the clear sky emittance (ϵ_c) and the clear sky surface downward long wave radiation ($LW_{cloudless}$). Using Eq. (2), it's possible to rewrite Eq. (1) as follows in Eq. (3). In summary, the LW and $LW_{cloudless}$ will have the same value for clear sky condition; otherwise, the LW will be larger than $LW_{cloudless}$ (Malek, 1997).

$$LW_{cloudless} = \epsilon_c \cdot \sigma \cdot T_a^4 \tag{2}$$

$$LW = LW_{cloudless} + \text{CCF}_{\text{LW}} \cdot (1{-}\in_c) \cdot \sigma \cdot T_c^4 \tag{3}$$

$$\text{CCF}_{\text{LW}} = (LW{-}LW_{cloudless})/(1{-}\in_c) \cdot \sigma \cdot T_c^4 \tag{4}$$

After some algebraic work, the CCF_{LW} can be estimated from Eq. (4). The T_c can be estimated using atmospheric physics and computational methods as described in (Malek, 1997). Furthermore, the $LW_{cloudless}$ value depends on the daytime and the air temperature. It was estimated taking the minimum LW value observed at the measurement site for the same timeframe of 1 h and for 5 °C interval of air temperature in the monthly meteorological dataset.

The values of CCF_{LW} should range from 0 (zero) for cloudless sky condition to 1 (one) for overcast conditions. However, the CCF_{LW} provided by Eq. (4) varies from negative values to positive values larger